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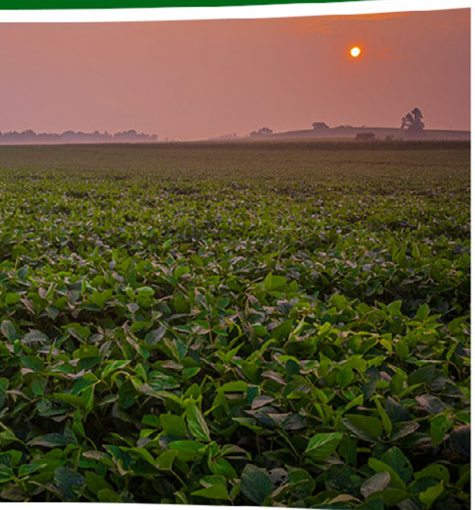
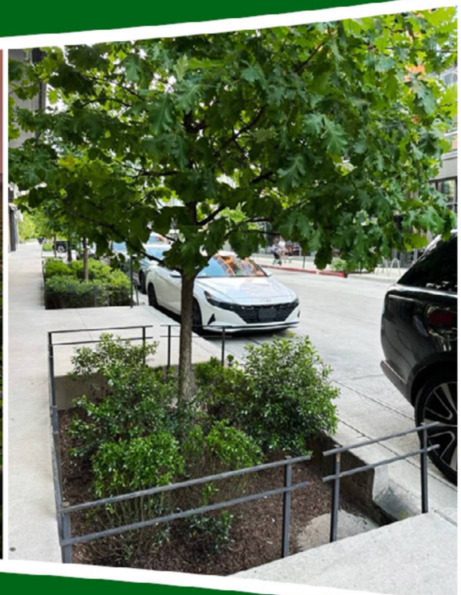


A Compendium of Tools and Methods to Estimate Environmental Benefits for Nature-Based Solutions

Environmental Benefits Related to Water Quantity, Climate Mitigation, Air and Habitat

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Acronyms and Abbreviations

ac-ft	acre-feet
ac-ft/yr	acre-feet per year
BMP	best management practice
BRAT	Beaver Restoration Assessment Tool
CH_4	methane
CN	curve number
CO_2	carbon dioxide
CSU	Colorado State University
gal/yr	gallons per year
GHG	greenhouse gas
GSI	green stormwater infrastructure
HMI	Heat Mitigation Index
in.	inches
kg	kilograms
kg C/m^2	kilograms of carbon per square meter
kg C/yr	kilograms of carbon per year
LID	low impact development
m^3/yr	cubic meters per year
MAR	managed aquifer recharge
Mgal/mi^2/yr	million gallons per square mile per year
N/A	not applicable
N_2O	nitrous oxide
NBS	nature-based solution
NO_2	nitrogen dioxide
O_3	ozone
PLET	Pollutant Load Estimation Tool
$PM_{2.5}$	particulate matter less than 2.5 microns
SO_2	sulfur dioxide
SWAT	Soil and Water Assessment Tool
SWMM	Storm Water Management Model
USDA	U.S. Department of Agriculture
USFS	U.S. Forest Service
USGS	U.S. Geological Survey
W/m^2	watts per square meter

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Introduction

State programs, cities and local communities develop plans and implement best management practices to address water quality impairments. Some best management practices may fall under the umbrella of nature-based solutions and provide social, economic and environmental outcomes, or benefits to communities and watersheds. Environmental benefits may be of particular interest when considering hazard mitigation and offsetting the impacts of land use change. The U.S. Environmental Protection Agency developed this easy-to-use resource for states, Tribes, local watershed groups and others interested in estimating environmental benefits, beyond water quality, at the planning level. This compendium connects urban and agricultural nature-based solutions to publicly available tools and methods that quantify environmental benefits related to water quantity, climate mitigation, air and habitat. The compendium will be updated periodically as new resources become available.

What are Nature-based Solutions and Environmental Benefits?

Land use changes and urbanization disrupt the natural hydrologic cycle and cause cascading effects such as degradation of water quality, localized and riverine flooding, increased air pollution and urban heat islands. These impacts are further exacerbated by climate change. Holistic solutions to mitigate these impacts need to integrate traditional gray infrastructure (e.g., storm pipes) with management practices that rely on natural processes (e.g., floodplain restoration and urban tree canopy).

The EPA defines **nature-based solutions (NBS)** as actions that protect, conserve, restore and sustainably manage natural or modified ecosystems. They use natural features or processes to address public health and environmental challenges while providing multiple benefits to people and nature. NBS encompass a wide range of actions that may include planning, design and maintenance of engineering practices that restore, use or enhance natural processes (e.g., green infrastructure, agricultural conservation practices and coastal restoration) or protect natural features to preserve ecosystem function (e.g., wetlands, forest, riparian areas and coral reefs).

NBS are often selected and designed to achieve a primary outcome while simultaneously delivering additional benefits. For the purposes of this document, **environmental benefits** occur when the design of NBS achieves benefits beyond the intended primary function of restoring or protecting water quality. For example, cover crops planted on an agricultural field to control erosion also provide carbon sequestration benefits. Other common terms used to describe environmental benefits include *co-benefits, ecosystem services, multiple benefits, stacked benefits, ancillary benefits* and *climate mitigation benefits.*

Compendium Purpose, Scope and Organization

The federal government has scaled up resources, funding and support to advance the implementation of NBS. This includes historic investments through the 2021 Infrastructure Investment and Jobs Act (P.L. 117-58, Nov. 15, 2021), also known as the Bipartisan Infrastructure Law, executive orders (e.g., EO 14008 and EO 14072) and policy directives such as the White House Nature-Based Solutions Roadmap. NBS align with *Clean Water Act* goals to restore, protect and preserve water quality and [the EPA's 2022–2026 Strategic Plan] to accelerate resilience and adaption to climate change impacts. Other federal agencies, such as the Federal Emergency Management Agency and the U.S. Army Corps of Engineers, support and prioritize planning and implementing NBS to achieve natural hazard mitigation and resilience goals. When managing nonpoint sources of pollution, aligning goals related to NBS in hazard mitigation plans and watershed-based plans help planners to leverage activities of mutual interest and achieve multiple benefits (i.e., water quality and resilience).

What is the scope? This compendium summarizes tools that grantees and sub-grantees may use at the planning level to quantify and communicate environmental benefits of NBS when implementing restoration- and protection-based management practices with funds from EPA's CWA Section 319 Grant Program and the Bipartisan Infrastructure Law, which funds the Gulf Hypoxia Program.[1] In addition, this resource may be valuable to others implementing NBS. During project planning, grantees, sub-grantees and communities may need to identify and quantify a project's primary outcome and other benefits (Table 1). However, informational resources that connect specific NBS to existing methods or tools that help quantify environmental benefits are lacking; this compendium aims to address that gap and presents details of varied methods and open-source tools. The EPA assessed a wide range of resources, including white papers, peer-reviewed journal articles, government web pages and other technical resources, to compile useful and constructive information available on NBS and environmental benefits. Appendix B discusses a component of the literature review. In general, users of the compendium can apply these relatively simple quantification methods and tools throughout the contiguous United States. This compendium is intended to be an informational resource and does not impose any binding requirements on grantees. Users who are considering applying any of the tools discussed here for programmatic or regulatory purposes should connect with their EPA Regional Office or State Regulatory Program on whether the tool(s) are appropriate to use.

Primary outcomes and additional environmental benefits will vary depending on the goals and factors of integrating NBS into a watershed. Table 1 lists benefit categories and specific environmental benefits most common in the Section 319 program. The list is not exhaustive but will be updated periodically as new tools and resources develop. Because water quality improvements are the primary driver of Section 319 and Gulf Hypoxia Program projects, water quality is not listed as a benefit in Table 1. The EPA's *Handbook for Developing Watershed Plans to Restore and Protect our Waters* and *Green Infrastructure Modeling Toolkit* web page provide an overview of watershed models available to estimate pollutant load reductions associated with NBS implementation for urban and agricultural land uses (EPA 2008a, 2023).

How is the document organized? This compendium is organized into four main sections specific to the benefit categories presented in Table 1. Each section consists of two parts. The first part presents a summary table that connects NBS to identified environmental benefits, quantification methods or tools, reported units and applicable project scale. The second part provides a brief description of each method or tool and points users to additional resources.

[1] "Restoration" refers to actions implemented to *reduce* existing pollutant loading to waterbodies, whereas "protection" refers to actions specifically implemented to preserve existing natural lands to *prevent* future pollutant loading to waterbodies. Refer to Appendix A for additional clarification.

Table 1. Summary of environmental benefits covered in the compendium with water quality as the primary outcome

Benefit Category	Specific Environmental Benefits
Water quantity	• Runoff reduction • Runoff prevention • Groundwater recharge potential • Rainfall interception
Climate mitigation	• Carbon emission reductions • Carbon storage • Carbon sequestration
Air	• Air quality improvement • Ambient air temperature reduction
Habitat	• Improved habitat scores or indices • Aquatic connectivity • Habitat creation • Riparian shading

Water Quantity Benefits

Some NBS capture and retain runoff to minimize the volume of runoff entering rivers and streams and reduce flooding risk. Runoff captured by NBS can be managed through natural hydrologic processes, such as evapotranspiration and infiltration, or stored for reuse. Table 2 highlights two methods and five tools that can be used to estimate water quantity-related benefits associated with urban and agricultural NBS.

The water quantity-related benefits considered here include the following:

Runoff volume prevented, which refers to preventing increased runoff as a result of future land use changes relative to runoff generated from existing natural land cover.[2]

Runoff volume reduction, which refers to runoff that is captured, intercepted, stored and retained by restoration-based NBS. Captured runoff volume can be subsequently managed through processes of infiltration, transpiration and evaporation or reused.[2]

Groundwater recharge potential, which applies to systems that capture and introduce runoff into the subsurface for infiltration and eventual migration to the water table.[2]

Rainfall interception, which describes the amount of precipitation captured by vegetation.[2]

[2] Icons made by Freepik from www.flaticon.com.

Table 2. Water quantity-related benefits, estimation tools and methods

Intervention Type	Method/Tool	Lead Agency	Applicable NBS	Benefit	Units	Scale
Protection	CN Method	N/A	Easement/land conservation		ac-ft/yr	Varies (site to watershed)
	i-Tree Canopy	USFS and cooperating partners[a]	Existing tree canopy		Mgal/mi^2/yr	Varies (parcel to watershed)
Restoration	PLET – Volume Reduction Method	EPA	GSI and LID		gal/yr	Varies (site to watershed)
	EPA National Stormwater Calculator	EPA	GSI and LID		in. (reported on a long-term annual basis)	Site (12 acres maximum)
	InVEST - Urban Stormwater Retention	Natural Capitals Project, 2024	Urban green spaces		m^3/yr	Watershed
	i-Tree Planting Calculator	USFS and cooperating partners[a]	Urban tree planting		gal/project lifetime	County, project level
	Green Roof Energy Calculator	Portland State University, University of Toronto, Green Roofs for Healthy Cities	Green roof		in.	Building
	CN Method	N/A	GSI and LID		ac-ft	Varies (site to watershed)
	CN Method	N/A	Agricultural BMPs		ac-ft/yr	Varies (site to watershed)

Notes: ac-ft/yr = acre-feet per year; CN = curve number; gal/yr = gallons per year; GSI = green stormwater infrastructure; in. = inches; LID = low impact development; Mgal/mi^2/yr. = million gallons per square mile per year; m^3/yr = cubic meters per year; N/A = not applicable; PLET = Pollutant Load Estimation Tool; USDA = U.S. Department of Agriculture; USFS = U.S. Forest Service.
[a] The i-Tree suite of tools is supported by the cooperative agreement between the U.S. Forest Service, Davey Tree Expert Company, The Arbor Day Foundation, Urban and Community Forestry Society, International Society of Arboriculture and Casey Trees.

Water quantity method and tools

The curve number (CN) method is an empirical method developed by the U.S. Department of Agriculture and is widely used to estimate the runoff response for a particular land use area (USDA 2004). The equation estimates runoff amount (Q, in.) as a function of rainfall depth (P, in.), potential maximum retention after runoff begins (S, in.) and initial abstraction (I_a, in.) (Equations 1–3 in Appendix C). S can be represented as a function of the CN—a unitless parameter that accounts for various hydrologic soil groups, land use type or treatment and antecedent soil moisture condition. Land use types include urban, cultivated agriculture, other agriculture and arid and semiarid rangeland uses. CNs range from 0 to 100; with higher CNs corresponding to increased runoff. The CN method was developed for a single event but can be scaled to determine annual average runoff.

The CN method can be used to estimate reductions in runoff resulting from changes in land use and soil conditions from different agricultural NBS such as cover crops, grass buffers and riparian buffers. Additionally, the CN method can estimate the annual runoff volume generated from a particular land use cover and available for groundwater recharge and potential managed aquifer recharge. Practices often used for managed aquifer recharge include infiltration basins, infiltration trenches, porous pavement, bioretention and dry wells. This method can be applied at the regional scale (state, county or watershed level) and at the site level. The EPA's *Enhanced Aquifer Recharge of Stormwater in the United States: State of the Science Review* synthesizes current scientific and technical literature surrounding managed aquifer recharge (EPA 2021). Table 4-2 in the report summarizes recharge volumes and infiltration rates from case studies across the United States. Managed aquifer recharge can pose risks to groundwater; appropriate site characterization and data collection is needed to determine the feasibility of a project.

EPA's Pollutant Load Estimation Tool (PLET) uses the CN method to estimate **runoff volume prevented** for protection-based NBS. The runoff volume prevented approach determines the difference in runoff volumes between an existing land use scenario (such as a forested land use) and a potential future land use scenario (such as conversion to urban land use). PLET also uses a **runoff volume reduction method** to estimate the volume of runoff captured by specific urban BMPs designated with "LID" for low impact development. Practices include cisterns, rain barrels, bioretention, dry wells, buffer strips, infiltration swales, infiltration trenches, vegetated swales and wet swales. This method considers the storage capacity of the BMP, the BMP drainage area (DA, acres), the design runoff depth to be captured by the BMP (RD, in.) and the runoff volume per storm event (P, in.) to determine an annual runoff volume reduction (Equations 4–6 in Appendix C).

InVEST's Urban Stormwater Retention model estimates urban runoff retention and potential groundwater recharge in response to annual precipitation for different land use types. NBS relevant to the model would include existing or planned natural land covers such as urban tree canopy or parks. Required model inputs include runoff coefficients, percolation coefficients and a raster of land use and landcover types. The Urban Stormwater Retention section of the InVEST user guide provides more details on the methodology.

i-Tree includes a suite of web-based and desktop tools developed to quantify the benefits of trees for a variety of user applications (Nowak 2021). The flagship tool, i-Tree Eco, contains all the detailed science and data inputs; in general, other i-Tree tools discussed here are simplified and faster versions of i-Tree Eco and apply multipliers determined from i-Tree Eco runs. Across the i-Tree suite, benefits quantified include water quantity, carbon, air quality and energy savings. Environmental benefits relevant to the scope of this compendium are highlighted for select i-Tree tools. Users are encouraged to explore the variety of i-Tree tools beyond what is highlighted here.

- **i-Tree Canopy** is a web-based tool used to assess the benefits of **existing tree canopy cover**. I-Tree canopy uses Google aerial imagery and a standard statistical point survey approach to determine cover types, such as tree cover, impervious, grass/shrub and so forth. The tool also includes a change analysis functionality that enables users to evaluate changes over time. Rainfall interception and avoided runoff are determined based on local weather data and a standardized volumetric removal rate based on the area of canopy cover (i.e., cubic meters per square meter, m^3/m^2).
- **i-Tree Planting Calculator** is a web-based tool commonly used to estimate the benefits of **tree planting projects** for numerous species. The input data requirements include information specific to the tree species type and diameter at breast height, distance of tree plantings from buildings, mortality rate and the project lifespan. Estimates for runoff reductions and rainfall interception use the same methodology as i-Tree Canopy, but results are reported for the project duration.

EPA's National Stormwater Calculator is a screening-level tool used to compute site hydrology (12 acres or less) under various land use scenarios. Users can determine runoff volume reduction for specific LID controls, including disconnection, rain harvesting, rain gardens, green roofs, street planters, infiltration basins and permeable pavement. Site hydrology is computed in the background using EPA's Storm Water Management Model (SWMM). The tool provides regionally adjusted capital and operations and maintenance costs and enables users to consider climate change scenarios for internationally recognized climate change projections.

Green Roof Energy Calculator is an online tool that estimates and compares the energy performance, heat flux, evapotranspiration and stormwater runoff volume reductions between a conventional roof and a green roof. The tool can be used for new and old residential and office buildings. The input data includes annual precipitation data for 100 cities in the United States and Canada. Runoff volume reductions are determined based on the user's inputs for the roof surface area, coverage of the green roof and soil media depth.

Climate Mitigation Benefits

"Climate mitigation" refers to interventions and actions that reduce greenhouse gas (GHG) emissions and protect or enhance carbon storage. Protection of forests and many vegetative agricultural NBS implemented by the Section 319 Program and the Gulf Hypoxia Program provide climate mitigation benefits. Table 3 lists eight tools to estimate emission reductions, carbon sequestration or carbon storage.

Climate mitigation-related benefits considered here include the following:

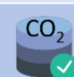
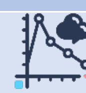
Emission reductions, which refers to interventions and actions that reduce GHGs (carbon dioxide [CO_2], nitrous oxide [N_2O] and methane [CH_4]) emitted into the atmosphere. In the context of agricultural conservation practices, emission reductions may result from changes in fertilizer management or biomass burning.[3]

Carbon sequestration (sometimes referred to as *biological carbon sequestration*), which refers to the natural uptake of CO_2 from the atmosphere by grasses, shrubs, trees and crops through the process of photosynthesis. Carbon sequestration is represented as a rate (mass per time).[4]

Carbon storage, which refers to the total carbon currently stored in vegetation or soil.[5]

[3] Icon made by inipagistudio from www.flaticon.com.
[4] Icon made by Freepik from www.flaticon.com.
[5] Icon made by Smashicons from www.flaticon.com.

Table 3. Climate mitigation-related benefits and estimation tools

Tool/Metric	Lead Agency/Org.	Applicable NBS	Benefit	Units	Scale
COMET-Planner	USDA and CSU	Agriculture conservation practices, pastureland conservation practices	 	Tons of CO_2 equivalents per year[b]	County
ALU National GHG Inventory Software	CSU, EPA, USAID and USFS	Agricultural and forest activities		Unknown	National
InVEST®-Carbon	Natural Capitals Project, 2024	Agriculture pastureland forest	 	Metric tons of C per pixel per year	Land parcel
CaRPE Tool	American Farmland Trust and USDA Agricultural Research Service	Agriculture conservation practices (6), pastureland conservation practices (4)		Tons of CO_2 equivalents per year	Varies (county to national scale)
FLR Carbon Storage Calculator	Winrock International	Agroforestry, natural regeneration		Tons of CO_2 stored per year	State
Cool Farm	Cool Farm Alliance	Reduced tillage, nutrient management, cover crops, reforestation		Kg CO_2 equivalents per year	Field
i-Tree Canopy	USFS and cooperating partners[a]	Protection of existing tree canopy	 	Storage: kg C/m^2 sequestration: kg C/yr	Varies (parcel to watershed)
i-Tree Planting Calculator	USFS[a]	Tree-planting projects		sequestration: kg C/project lifespan	County, project level

Notes: ALU = agriculture and land use; CSU = Colorado State University; kg C/m^2 = kilograms of carbon per square meter; kg C/yr = kilograms of carbon per year; USAID = U.S. Agency for International Development; USFS = U.S. Forest Service.

[a] The i-Tree suite of tools is supported by the cooperative agreement between the USDA Forest Service, Davey Tree Expert Company, The Arbor Day Foundation, Urban and Community Forestry Society, International Society of Arboriculture and Casey Trees.

[b] CO_2 equivalents is a metric that compares emission of CO_2, N_2O, and CH_4. CO_2 is based on each gas's global warming potential, or the climate forcing of 1 kg of GHG emission to 1 kg of CO_2.

Climate mitigation tools

COMET-Planner is a web-based tool designed for initial planning purposes and provides an estimate of the potential carbon sequestration and GHG emission reductions of conservation practices at the county level. Results are reported as CO_2 equivalents in tons of CO_2 per year. Practices within COMET-Planner have an associated emission reduction coefficient for CO_2, N_2O and CH_4 that is derived from a sample-based approach and COMET-Farm model runs. The USDA Natural Resources Conservation Service provides a list of NBS that may deliver quantifiable reductions in greenhouse gas emission and/or increase carbon sequestration on the COMET-Planner web page. The *COMET-Planner Report* provides detailed information on the quantification methods behind the tool (USDA and CSU 2022).

The **Agriculture and Land Use (ALU) National Greenhouse Gas Inventory Software** estimates carbon emissions and removals associated with biomass and soil in addition to N_2O emissions (soil and manure) and CH_4 emissions (rice, enteric and manure). Methods stem from the Intergovernmental Panel on Climate Change. The program can be downloaded from the tool web page.

The **InVEST Carbon Storage and Sequestration model** is a simple carbon model that estimates the annual carbon storage for existing land cover and future land cover scenarios. The tool can be used to assess changes in carbon storage overtime between existing and future land use scenarios and relies on land cover maps for inputs. The tool was designed to assist decision-makers with natural resource management. Because the model is map-based, mapping software such as ArcGIS is needed. More details can be found on the InVEST Carbon page.

CaRPE Tool, or the Carbon Reduction Potential Evaluation Tool, is a web-based tool that couples emission reduction coefficients from COMET-Planner with cropland and grazing data from the Census of Agriculture (2012, 2017, or 2022) to estimate GHG reductions at the county, state, regional or national scale. CaRPE can map current and future GHG reductions from conservation practice adoption. The visual interface allows users to view results via table and map displays.

FLR Carbon Storage Calculator is a global tool that estimates carbon storage based on the hectares of annual planted or restored vegetation for the following activities: agroforestry, plantation operations, natural regeneration and mangrove restoration. Estimates are based on literature-derived bioaccumulation rates (carbon dioxide, CO_2, per hectare per year) for the listed activities (Bernal et al. 2018).

Cool Farm Tool Online, developed by Cool Farm Alliance, is a web-based tool that provides GHG emission estimates for a specific product at the farm scale (Cool Farm Alliance 2024). The tool can account for reduced tillage, nutrient management, cover crops and tree planting. Unlike other climate mitigation tools identified in the compendium, Cool Farm accounts for other direct field emissions, including combustion of diesel and indirect emissions such as transport. Methodologies in the tool primarily stem from the Intergovernmental Panel on Climate Change (IPCC 2006, 2019).

i-Tree Canopy uses percent tree cover to determine annual estimates of carbon storage using a nationalized CO_2 storage rate (7.69 kg/m^2). Carbon sequestration is determined using state-specific sequestration rates ($kg\ C/m^2/yr$) (Nowak et al. 2013). Refer to the Water Quantity section of this compendium for more background details on i-Tree Canopy.

i-Tree Planting Calculator estimates carbon sequestration over the designated lifespan of a tree-planting project based on species-specific biomass equations. Refer to the Water Quantity section of this compendium for more background details on i-Tree Planting Calculator.

Air Benefits

This section presents tools for air quality improvements and ambient air temperature reduction benefits.

Air quality improvements

Increased traffic density in urban centers contributes to air pollution and areas of elevated exposure alongside roadways and other air pollution sources (e.g., Karner et al. 2010). Air quality benefits described in this section refer to air quality improvements by trees and other vegetation for gaseous and particulate-borne pollutants. While the protection or planting of urban tree canopy and other vegetation can improve air quality, the impact varies from the local to the regional scale. At the local scale, air quality benefits are complicated by site-specific factors. Refer to the section Local Scale Considerations for Air Quality Benefits for resources that discuss more about site-specific factors that influence green stormwater infrastructure (GSI) air quality benefits in urban settings. At the regional scale, studies demonstrate the reduction of air pollution via leaf surfaces from tree canopy and vegetation (Janhall 2015; Gallager et al. 2015). Table 4 lists two tools available for estimating air quality benefits at the regional and county scale.

Table 4. Air quality benefits and estimation tools

Tool	Lead Agency/Org.	Applicable NBS	Benefit	Units	Scale
i-Tree Planting Calculator	USFS[a]	Tree canopy planting	Air quality improvement	Pounds or kg/project lifespan	County, project level
i-Tree Canopy	USFS[a]	Protection or management of existing tree canopy	Air quality improvement	Tons/year	Varies (parcel to watershed scale)

Note: kg = kilograms; USFS = U.S. Forest Service.
[a]The i-Tree suite of tools is supported by the cooperative agreement between the USDA Forest Service, Davey Tree Expert Company, The Arbor Day Foundation, Urban and Community Forestry Society, International Society of Arboriculture and Casey Trees.

Regional scale air quality tools

i-Tree Planting Calculator estimates air pollution reductions for ozone (O_3), nitrogen dioxide (NO_2), sulfur dioxide (SO_2) and particulate matter less than 2.5 microns ($PM_{2.5}$). Air pollutant reductions are reported in pounds or kilograms for the total project lifespan specified by the user. Air pollutant removal values are derived from i-Tree Eco runs using air pollution and weather data at the county level. Refer to the Water Quantity section of this compendium for more background details on i-Tree Planting Calculator.

i-Tree Canopy applies the same methodology as i-Tree Planting Calculator to determine annual air pollutant reductions of carbon monoxide, NO_2, O_3, SO_2, $PM_{2.5}$ and particulate matter less than 10 microns for an area of existing tree cover (Nowak 2021). Refer to the Water Quantity section of this compendium for more background details on i-Tree Canopy.

Local-scale considerations for air quality benefits

At the local scale, roadside vegetation type and placement influence whether vegetation reduces or increases air pollution in urban environments. To achieve air pollution benefits, vegetation along roadways and near other air pollution sources must have full coverage from the ground to the top of the canopy with low porosity and high leaf-area density. If gaps between the vegetation or areas of high porosity exist, air pollutants can accumulate within and beyond the canopy, leading to increased local air pollution levels. In addition, vegetation near air pollution sources needs to be sufficiently tall and thick to promote air pollution capture and increased wind turbulence to improve local air quality. While tools are not yet available to quantify the impacts of GSI along roadways and other air pollution sources, the following resources highlight important characteristics needed to inform design decisions and optimize air quality benefits:

- **Recommendations for Constructing Roadside Vegetation Barriers to Improve Near-Road Air Quality:** This report identifies qualitative characteristics and best practices to improve air quality when implementing vegetation along roadsides (Baldauf 2016).
- **The effects of roadside vegetation characteristics on local, near-road air quality:** This review article provides estimates of air pollution reductions under differing vegetation characteristics (Deshmukh et al. 2019).
- **Air pollution abatement performances of green infrastructure in open road and built-up street canyon environments – A review:** This review focuses on the effect of tree canopy, sedges, green walls and green roofs on air quality in street canyon and open road settings (Abhijith et al. 2017).

Ambient air temperature reduction

Because of the higher density of buildings and pavement in urban environments, developed settings absorb and reemit more heat than natural land covers. The release of heat in urban environments creates pockets of higher temperature on surfaces and in the air referred to as “heat islands.” Heat islands can contribute to compromised human health and increased temperatures of urban runoff, which can lead to thermal pollution and the degradation of habitat in nearby rivers and streams. Ambient air temperature reductions refer to temperature reductions provided by trees, vegetation and green roofs through processes of shading and evapotranspiration (EPA 2008b). Table 5 lists three tools for estimating ambient air temperature reductions.

Table 5. Air temperature reduction benefits and estimation tools

Tool	Lead Agency/Org.	Applicable NBS	Benefit	Units	Scale
InVEST – Urban Cooling	Natural Capital Project, 2024	Urban green spaces (i.e., tree canopy and urban parks) > 2 ha	Urban Heat Mitigation Index	Unitless (0–1)	City
i-Tree Research suite; Cool Air	USFS[a]	Tree canopy	Ambient air temperature reduction	˚F	Varies (local, city, regional)
Green Roof Energy Calculator	Arizona State University, Toronto University and Green Roofs for Healthy Cities	Green roofs	Latent and sensible heat flux	W/m^2	Building level

Notes: ˚F = degrees Fahrenheit; ha = hectares; W/m^2 = watts per square meter.
[a]The i-Tree suite of tools is supported by the cooperative agreement between the USDA Forest Service, Davey Tree Expert Company, The Arbor Day Foundation, Urban and Community Forestry Society, International Society of Arboriculture and Casey Trees.

Ambient air temperature reduction tools

InVEST's Urban Cooling model estimates the cooling effect of green spaces (more than 2 hectares in area) on surrounding land covers using the Heat Mitigation Index (HMI). The HMI is determined based on the cooling capacity, a function of shade, evapotranspiration and albedo, for each land cover grid cell in the study area. Cooling capacity is a unitless number ranging from 0 to 1 where "0" represents no cooling capacity and "1" represents maximum cooling capacity. HMI equals the cooling capacity if the pixel is unaffected by green space or equals a weighted average of the cooling capacity values along the distance from the green space to the area of interest. The Urban Cooling section in the InVEST User Guide provides more detail on the methodology. HMI is displayed on a map. Similar to the InVEST Carbon Storage and Sequestration model, mapping software such as ArcGIS is needed.

i-Tree Cool Air is a spatial air temperature model that is a component of the i-Tree Research Suite. i-Tree Cool Air simulates the impact of land use and tree cover on air temperature and humidity. The tool requires the use of a geographic information system to display outputs and can evaluate air temperature effects at the local and regional scale.

Green Roof Energy Calculator is an online tool that compares the energy performance, heat flux, evapotranspiration and stormwater runoff reductions between a conventional roof and a green roof. The tool can be used for residential and office buildings and includes input data for 100 cities in the United States and Canada. Latent heat is felt as humidity and is represented in units of watts per square meter (W/m^2). Sensible heat flux describes the temperature difference between the roof surface and surrounding air and also is represented in units of W/m^2. Green roofs result in an increase in latent heat and a decrease in sensible heat flux, which results in a cooling effect.

Habitat Benefits

Habitat benefits can be realized when NBS create, protect or restore habitat for wildlife and ecological function. Quantification of habitat is more nuanced than other environmental benefits previously described because it can be represented by a variety of indicators or metrics such as a habitat quality score, vegetation diversity, abundance of wildlife or miles of stream length connected for fish passage. Table 6 summarizes qualitative tools or metrics to communicate habitat benefits.

Table 6. Habitat related benefits, estimation tools and metrics

Benefit Tool/Metric	Lead Agency/Org.	Applicable NBS or land use types	Units	Scale
Habitat Potential Index	Field to Market's Field Print Platform (partnered w/ USGS)	Cropland, pastureland, forest and wetlands	Unitless (0–100)	Field/farm scale
InVEST Habitat Quality	Natural Capitals Project, 2024	Protection of existing natural land cover	Unitless (0–1)	Watershed
Beaver Restoration Assessment Tool (BRAT)	Utah State University	Stream conservation and restoration	Varies	Watershed or regional
Database of biodiversity, habitat, and aquatic resource quantification tools	USGS and EPA	Conservation and compensatory mitigation	Varies	Varies
Habit protected	N/A	Conservation easements, land acquisition wetland protection	Examples include: • Acres of wetland protected • Acres of open space	Varies
Habitat created	N/A	GSI, cropland and pastureland NBS	Examples include: • Acres of greening from GSI • Acres of tree canopy	Varies
Aquatic connectivity	N/A	Dam removal, road stream crossing removal or replacement with ecological function	Example units include: • Stream miles connected for fish passage • Stream miles of restored floodplain connection	Varies

Notes: N/A = not applicable; USGS = United State Geological Survey; GSI = green stormwater infrastructure.

Habitat assessment tools and metrics

The **Habitat Potential Index** for Biodiversity provides a qualitative assessment of the effect of agricultural land use on habitat quality and quantity. Both production and nonproduction lands are considered. The index ranges from 0 to 100 and is meant to promote protection and/or enhancements of existing habitat. For example, a score less than 50% indicates more opportunities exist to improve habitat. More information about the Habitat Potential Index Score can be found in Field to Market's Harnessing Sustainability Insights & Unleashing Opportunity.

InVEST's Habitat Quality model maps the biodiversity of a landscape by coupling land use data with threats to biodiversity. The model displays habitat quality scores as a proxy for biodiversity. Habitat quality is a qualitative unitless number that ranges from 0 to 1 where "0" indicates poor habitat suitability and "1" indicates high habitat suitability. The habitat quality score is a function of several factors that include the relative impact of each threat, the impact across the distance between the threat and the habitat, whether the habitat is protected from disturbance, and the sensitivity of habitat type to threats on the landscape. The model can be used to evaluate the impact of different land use changes or management scenarios on biodiversity relative to a baseline.

Beaver Restoration Assessment Tool (BRAT) is a planning-level tool that consists of spatial models to predict the potential for beaver dam building activity. BRAT can be used at the watershed or regional scale. Outputs of the tool provide information for each stream segment, including beaver dam capacity (units of dams per kilometer or mile) and estimated beaver dam complex or the maximum number of beaver dams. The tool also provides management information such as habitat limitations to beaver dams, undesirable beaver dam locations and beaver dam opportunities.

Database of biodiversity, habitat, and aquatic-resource quantification tools used in market-based conservation in the United States summarizes attributes of 107 quantification tools developed for market-based conservation, non-compensatory mitigation, and voluntary conservation and restoration programs within the United States (Chiavacci et al. 2022). The database is presented in a downloadable spreadsheet format and describes 33 different attributes, including locations of use, user skill level, focal habitat, data inputs and output types.

Habitat created refers to restoration NBS that add, create or extend natural ecosystems to increase biodiversity. Habitat created can be reported as a unit area of land cover.

Habitat protection refers to protection interventions that protect and prevent the loss of natural ecosystems from future development or land disturbance. Similar to habitat created, habitat protected can be reported as a unit area of land cover.

Aquatic connectivity is defined by the U.S. Fish and Wildlife Service as physically linked pathways through which energy, matter and organisms move from one place to another through water. It includes longitudinal connectivity upstream and downstream and vertical movement within a water column as well as lateral connectivity of the main waterbody to riparian and floodplain habitat, all of which play a vital role in a functioning aquatic ecosystem (USFWS 2021). Aquatic connectivity can be reported using a variety of metrics such as stream length opened for aquatic passage or stream length with floodplain connectivity.

Conclusion

This compendium connects NBS to environmental benefits and associated estimation methods or tools related to water quantity, climate mitigation, air and habitat. Readers can use this resource to estimate environmental benefits for activities such as:

- Preparing watershed-based plans;
- Writing grant proposals;
- Screening NBS;
- Communicating the benefits of NBS; and
- Evaluating or informing management actions or decisions.

Depending on the NBS and their scale, estimating multiple environmental benefits may necessitate the use of more than one tool. For example, i-Tree and InVEST estimate environmental benefits in more than one benefit category whereas COMET-Planner is specific to climate mitigation benefits only. Additionally, when summarizing multiple environmental benefits for the activities mentioned above, users of this compendium should pay attention to the various units across benefit categories and tools (Tables 2–5). For example, units may vary by the quantification metric for a benefit category (e.g., million gallons per square miles per year [$Mgal/mi^2/year$] versus cubic meters per year [$m^3/year$] for runoff retention) or by time (e.g., benefits quantified for a year versus a project lifespan).

The EPA intends to update this document periodically to incorporate tool enhancements and add new tools and other resources as they are developed. Many of the tool web pages identified in the compendium provide training videos and other support materials. Additionally, American Farmland Trust organized an Outcomes Estimation Tools Training Webinar Series that includes some tools described here including COMET-Planner and Cool Farm.

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Appendix A: Restoration versus Protection Actions

Table A.1 Distinction between restoration and protection NBS intervention.

Table developed by EPA 2024

Intervention Type	As Defined with respect to Waterbody Condition	As Defined with respect to Best Management Practices or NBS
Protection	Waterbodies that continue to meet water quality standards for one or more pollutants and/or designated uses.	Management actions specifically implemented to preserve existing natural lands to **prevent** future pollutant loading to waterbodies, such as: • Land conservation; • Wetland protection; and • Riparian area protection.
Restoration	Waterbodies that meet water quality standards for one or more pollutants and/or designated uses after being previously included on the Clean Water Act Section 303(d) list of impaired waters.	Management actions implemented to **reduce** existing pollutant loading to waterbodies, such as: • Green stormwater infrastructure; • Conservation tillage; and • Floodplain restoration

Appendix B: Literature Review – Systematic Abstract Screening

The EPA conducted a systematic abstract screening of peer-reviewed literature for urban-related nature-based solutions (NBS). The primary objectives of the abstract screening included (1) to assess the most frequently reported environmental benefits and (2) to screen methods to monitor or quantify environmental benefits.

This appendix summarizes the methodology and results of the screening. A total of 478 abstracts were collected and analyzed based on the inclusion criteria described in the following Methodology section. In summary, field and modeling studies were the top two study categories. For modeling studies, abstract screening identified various methods for quantifying environmental benefits. While most of the studies pointed to complex models (i.e., high data input requirements and best used for design and NBS sizing), studies also used simpler tools (i.e., low input data requirements and best used for the screening and planning level) such as InVEST and the i-Tree suite of tools. Findings from the systematic abstract screening informed the expansion of the literature search to include white papers, government web pages and other resources to identify simple and publicly available tools.

Methodology

The literature pull for the systematic abstract screening was conducted in Web of Science. Colandr, an open-source literature screening platform, was used to screen abstracts. Articles were included that met the following criteria:

- The article had to pertain to one of the following NBS: bioretention, green roof, permeable pavement, tree trenches, vegetated swale, rainwater harvesting, tree canopy, floodplain restoration, riparian buffers, constructed wetland, green wall, grassed waterway or sediment basin
- The study had to measure or quantify one or more of the following environmental benefits: flood mitigation, event flow reduction, evapotranspiration, groundwater recharge, thermal pollution mitigation, heat island mitigation, erosion control, water reuse, runoff retention, pollutant removal, climate change adaptation, recreational space, improved air quality, ecological flow or biodiversity

Included articles were documented in a spreadsheet based on the screening tags noted below. The spreadsheet is available from the EPA upon request. Power BI was used to visualize results.

Search Strings

The following search strings were used in Web of Science Core Collection on February 24, 2022, and April 5, 2022, which resulted in a return of 2,964 articles. Meta data for the articles were imported into Colandr, where 429 duplicates were removed for a total of 2,535 articles.

- <u>Search string NBS type, co-benefit, and evaluation (February 24, 2022) returns = 1,557</u>
  (TS=("bioretention" OR "rain garden" OR "permeable pavement" or "green roof" OR "tree trench" or "vegetated swale" or "rainwater harvesting" or "tree canopy" or "green wall" or "sediment basin" or "grassed waterway" or "constructed wetland" or "wetland" or "floodplain restoration" or "riparian buffers")) AND (TS=("co-benefits" or "benefits" or "ecosystem services")) AND (TS=("evaluation" or "framework" or "assessment" or "monitoring"))

- Search string NBS type, co-benefit, and climate change (February 24, 2022)
  Returns = 879
  (TS=("bioretention" OR "rain garden" OR "permeable pavement" or "green roof" OR "tree trench" or "vegetated swale" or "rainwater harvesting" or "tree canopy" or "green wall" or "sediment basin" or "grassed waterway" or "constructed wetland" or "wetland" or "floodplain restoration" or "riparian buffers")) AND (TS=("co-benefits" or "benefits" or "ecosystem services")) AND (TS=("climate change" or "climate adaption" or "resilience" or "climate mitigation"))
- Expanded search for bioretention and permeable pavement using the keywords noted below (April 5, 2022)
  Returns = 528
  (ALL=("bioretention" OR "biofiltration" OR porous pavement OR pervious concrete OR "bioswale" OR "grassed swale" OR "tree pit")) AND ALL=("co-benefits" OR "benefits" OR "ecosystem services" OR "climate change" OR "climate adaption" OR "resilience" OR "climate mitigation")

Screening Tags

Included articles were documented in a spreadsheet using the following screening tags.

Country:
- US; state
- not US; country

Nature-Based Solutions:
- bioretention/rain garden
- green roof
- permeable pavement
- tree trenches
- vegetated swale
- rainwater harvesting
- tree canopy/urban trees
- green wall
- grassed waterway
- sediment basin
- floodplain restoration
- riparian buffers
- constructed wetland

Study Type:
- field
- laboratory
- modeling
- case study
- review

Environmental Benefit:
- flood mitigation
- event flow reduction
- pollutant removal
- evapotranspiration
- groundwater recharge
- thermal pollution mitigation
- heat island mitigation
- water reuse
- runoff retention
- climate change adaption
- improved air quality
- ecological flow (base flow)
- biodiversity
- carbon sequestration
- dis-services/failures

Assessment Tool:
- monitoring
- modeling
- monitoring and modeling
- life cycle assessment
- cost/benefit analysis
- metanalysis
- evaluation framework

Results

The EPA screened 76 percent of the 2,535 pulled abstracts. A total of 478 abstracts were included. Table B.1 shows a heat map of the count of articles that quantified specific environmental benefits for the most frequently reported NBS in the included abstracts. Green roofs, bioretention, constructed wetlands, permeable pavement and NBS treatment trains were the most studied types of NBS. "NBS treatment trains" refers to more than one NBS solution in series. The "Other" column represents all other NBS types considered (see the nature-based solutions screening tags on the previous page).

Table B.1 Heat map of NBS and reported benefits for systematic abstract screening.

Darker shades of green correspond to higher article counts.

BMP Practice (groups)	Bioretention	Green roof	Constructed wetland	Permeable pavement	NBS treatment train	Other
Carbon sequestration	1	1	1	0	0	1
Climate change adaption	25	11	5	4	1	38
Ecological flow (base flow)	0	0	0	0	0	1
Erosion control	0	0	0	0	0	0
Evapotranspiration	9	16	0	0	0	7
Event flow reduction	19	8	4	4	2	26
Flood mitigation	11	2	8	0	0	29
Groundwater recharge	9	0	3	0	0	12
Habitat/biodiversity	8	18	21	0	0	14
Heat island mitigation	0	42	2	3	1	18
Improved air quality	1	6	6	0	0	9
Pollutant removal	48	9	45	11	2	65
Recreational space	1	0	1	0	0	2
Runoff retention	41	30	4	13	2	67
Trade-offs	29	14	17	6	0	45
Water reuse	1	1	1	0	0	1

Field and modeling studies were the top two study categories. For field studies, monitoring was the predominant assessment method. For modeling studies, EPA SWMM and Soil and Water Assessment Tool (SWAT) were the predominant assessment tools. Abstracts documented the use of both models to quantify flood mitigation, runoff retention, event flow reduction, groundwater recharge, water reuse, pollutant removal, climate change adaptation and trade-offs. In addition to these advanced models, abstracts also reported the use of simple tools such as InVEST, i-Tree Eco and i-Tree canopy.

Appendix C: Referenced Equations

Curve Number

Runoff amount (Q in., Equation 1) is estimated as a function of rainfall depth (P, in.), potential maximum retention after runoff begins (S, in.) and initial abstraction (I_a, in, Equation 2). S can be represented as a function of the curve number (CN)—a unitless parameter that accounts for various hydrologic soil groups and land use types including urban, cultivated agriculture, other agriculture, and arid and semiarid rangeland uses (Equation 3).

$$Q = \frac{(P-I_a)^2}{(P-I_a)+S} \qquad \text{Eq. 1}$$

where:

$$I_a = 0.2S \qquad \text{Eq. 2}$$

$$S = \frac{1000}{CN} - 10 \qquad \text{Eq. 3}$$

The Runoff Reduction Methods

This method considers the storage capacity of the BMP, the BMP drainage area (DA, acres), the percent imperviousness within the drainage area (PI, %), the design runoff depth to be captured by the BMP (RD, in.), and the runoff volume per storm event (P, in.) to determine an annual runoff volume reduction (Equations 4–6). Refer to the Model Documentation section the PLET web page for more details.

$$BMP_{storage}\ (ac-ft) = DA * PI * \frac{RD}{12} \qquad \text{Eq. 4}$$

$$Runoff_{vol}\ (ac-ft) = DA * PI * \frac{P}{12} \qquad \text{Eq. 5}$$

$$Runoff_{red.} = minimum\ (BMP_{storage}, Runoff_{vol}) \qquad \text{Eq. 6}$$